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Radiation Sensitivity of Unique Memory Devices

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14. ABSTRACT
Working protonated gate MOSFET transistor memories with gate lengths down to 5 microns and gate oxide thicknesses down to 20 nm have been produced using standard Si-based technological steps. Hysteresis in the source-drain current-versus-gate voltage as large as - 11 V was measured in 40 nm gate oxide transistors. The sensitivity of the memory to X rays was measured using an ARACOR source up to total accumulated doses of 2 Mrad (SiO2). No variation in the hysteresis voltage (which would correspond to a loss of protons) was ascertained, nor was there measurable data loss (by deviation of the current/voltage characteristic which would result if the protons redistributed themselves in the gate oxide). A buildup of fixed oxide charge in the gate oxide due to irradiation was measured and it was characteristic of that expected in an unhardened oxide.

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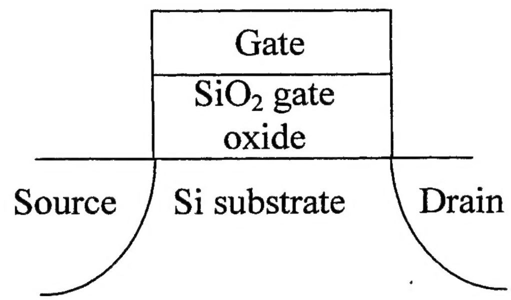
Introduction

In 1997 Vanheusden and co-workers[1] published a report in which they showed that under certain circumstances the annealing of $Si/SiO_2/Si$ structures in hydrogen containing atmospheres resulted in the appearance of stable, mobile positive charges which they identified as protons. These charges could be swept from one side of the structure to the other by application of relatively small electric fields (~ 1 MV cm^{-1} for example). The initial measurements were carried out on materials designed for silicon-on-insulator applications such as "BESOI", "SIMOX" and "Unibond" and the typical oxide thickness was ≥ 200 nm. It appeared that for materials of this thickness, once the protons were driven to one SiO_2/Si interface or the other, they remained there after removal of the electric field used to drive them to that position.

Figure 1. Simplified cross section of a MOSFET showing the source/drain contacts and the gate structure.



In Figure 1. We show a very simplified cross-sectional image of a metal-oxide-semiconductor field effect transistor (MOSFET). The key to the operation of this device is that application of an electric field across the oxide and semiconductor depletion layer (due to a potential between the gate electrode and the substrate/source contact) results in the creation of an inversion layer in the Si substrate layer adjacent to the Si/SiO_2 interface. A potential then applied between the source and drain contacts results in a current flow through the inversion layer. For the case of p-type Si, the inversion layer is comprised of electrons and this will be the

case we will deal with primarily in our work. The inversion is generated by application of a positive bias on the gate electrode, equivalent to placing positive charges in close proximity to the bottom Si/SiO_2 interface. It is apparent from Figure 1. that the gate structure of the MOSFET is similar to that discovered by Vanheusden et al[1] which enabled the "generation" and storage of mobile, positively charged protons though usually the oxide is substantially thinner, $\leq$ 40 nm. Practically, the thinner oxides associated with MOSFET structures can be made "proton receptive" if certain thermal processes are carried out following the production of the $Si/SiO_2/Si$ structure. The data on thick oxides suggested that the protons remained stably positioned after removal of the polarizing voltage so that the integration of mobile protons into the gate oxide of a MOSFET offers the interesting possibility of creating a transistor with an in-built memory capacity. Consider the two modes indicated in Figures 2a and 2b:

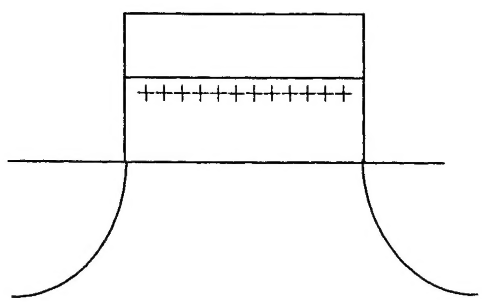


Figure 2a

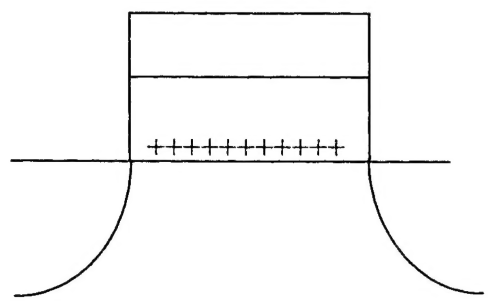


Figure 2b

In Figure 2a, the protons have no effect on the electrical characteristics of the device. The reason for this is that the effective "voltage" on the gate electrode due to the presence of charges in the oxide is given by:

$$\Delta V_{th} = - Q_{ot}/C_{ox} = - (1/C_{ox})[1/d_{ox}] \int \rho(x)\, x\, dx \qquad (1)$$

where C_{ox} is the gate oxide capacitance, Q_{ot} is the oxide trapped charge, $\rho(x)$ is the volume density of charge in the oxide and the integral is taken from 0 to d_{ox} (the oxide thickness) measured from the gate electrode. Clearly, if the protons are located in a delta function film at the gate electrode (Fig. 2a) then $\Delta V_{th} = 0$. If the protons are in a finite thickness δ at the oxide/substrate interface (Figure 2b), then ΔV_{th} is maximized at:

$$\Delta V_{th} = - \rho(0)\, \delta d_{ox}/\varepsilon\varepsilon_o$$

where $\rho(0)$ is the volume density of protons in the thickness, δ and $\varepsilon\varepsilon_o$ is the dielectric constant of the gate oxide.

For a MOSFET the source-drain current, I_{ds}, at small source-drain voltage (V_{ds}) is written:

$$I_{ds} = (Z/L)\, C_{ox}\, \mu_n\, [V_G - V]\, V_{ds} \tag{2}$$

where Z is the inversion channel width, L its length and μ_n the inversion channel carrier mobility. V_G is the voltage applied to the gate electrode. V can be written:

$$V = - Q_{ot}/C_{ox} + B \tag{3}$$

where B are transistor material dependent parameters[2]. When $V_G < V$ the transistor is "off" and no source-drain current flows. We see that when $- Q_{ot}/C_{ox}$ is zero (case of protons at the gate electrode/oxide interface) the transistor switches on when $V_G = B$. When the protons are at the substrate/oxide interface, the transistor switches on when $V_G = - Q_{ot}/C_{ox} + B$. In consequence, the protons can induce a hysteresis in the I_{ds} versus V_G curve. This hysteresis potentially serves the purpose of transforming the standard MOSFET into a device with an integrated memory function relying upon the source-drain current I_{ds} at a chosen V_G to ascertain whether the protons are located at the gate electrode/oxide interface or the oxide/substrate interface. The possibility

of manufacturing a "pseudo" non-volatile memory in this manner has formed the basis of a patent[3].

The present contract required us to manufacture MOSFET transistors with "realistic" gate oxide thicknesses which demonstrate the memory effect when protons are integrated into the oxide. Subsequently, an investigation of the radiation sensitivity of these devices was required. We have succeeded in manufacturing working MOSFET transistors with gate oxide thicknesses of 20 nm and 40 nm and gate lengths down to 5 μm. We have also succeeded in introducing protons into the gate oxide and tested the hypothesis that they can indeed be used to generate transistors with an inherent memory function. We have further examined the radiation sensitivity of such transistors in order to see whether or not the protons, and hence the memory, are "radiation hard".

Experimental

Dry gate oxides, either 20 or 40 nm thick, were grown at 900 °C on p-type Si <100> at Sandia National Laboratories (MDL) using standard technological methods. A 200 nm thick polycrystalline Si film was deposited on the grown oxide surface and then implanted with 3 x 10^{15} cm^{-2} P^+ ions at 40 keV. Transistor gate electrodes were then defined lithographically (L= 5-70 μm, Z = 100 μm) in the polycrystalline Si layer and the excess Si removed using an isotropic etch (XeF_2 gas). The wafer was then coated in a new layer of photoresist and gate source and drain contacts were defined. Wet chemical (BE 20:1- HF acid solution) was used to etch away the SiO_2 in the source/drain contact areas to reveal the Si substrate in these regions. Subsequently, the wafers were again implanted with 3 x 10^{15} cm^{-2} P^+ ions at 40 keV (to create the source and drain contacts) and the photoresist then removed in acetone. The wafers were

then annealed at 1000 °C in flowing N_2 or Ar for periods between 3 and 25 minutes in order to activate the dopants in the gate and source/drain regions and to simultaneously perform the important "degradation" step necessary for proton generation in the gate oxide[1]. Finally, the completed wafers were annealed in a 5% H_2N_2 gas mixture at 700 °C for 30 minutes before rapid cooling to room temperature. The latter process is known[1] to generate the protons if the wafers have received the important > 1000 °C prior degradation step.

Following processing, MOSFETs with protonation treatment were characterized electrically. Devices were studied using a Hewlett Packard 4145 A transistor characterization instrument. The devices were operated in the so-called linear mode (Equation 2) in which $I_{ds} \propto V_{ds}$ and V_G – typical values of V_{ds} were 0.2 – 0.6 V whilst the gate voltage (with respect to the source/drain) was swept from a maximum of –10 V to + 10 V depending upon the gate oxide thickness. In order to ensure that the protons were at the substrate/oxide (gate electrode/oxide) interface, positive (negative) sweeping voltages were applied to the gate electrode for periods up to 90 seconds prior to measuring I_{ds} as a function of V_G with V_G swept from positive (negative) to negative (positive) voltage in ~ 2 sec. The magnitude of the sweep was, again, dependent upon the thickness of the gate oxide being used in the study.

For the irradiation studies, the devices were mounted in an ARACOR system and irradiated with X rays from a tungsten target, the accelerating voltage was 50 kV. The dose rate was 260 rads (SiO_2) sec^{-1} and accumulated doses up to 2 Mrad we acquired. Devices were characterized electrically in situ in the ARACOR machine using the HP 4145 A system.

Results

Measurements have been made on a variety of devices with different channel lengths and with different gate oxide thicknesses (20 and 40 nm). Data on the retention time and switching as a function of applied electric field in the gate oxide can be found in the literature, this work is not the subject of the present study[4,5]. An example of a typical hysteresis in the I_{ds} versus V_G curve is, however, shown in Figure 3. This data, for a MOSFET made using a 40 nm gate oxide, was obtained by first polarizing the gate at + 8V for 30 seconds then sweeping V_G down to – 8 V in ~ 2 sec. (down arrow, full curve). The device was then polarized at – 9 V for 30

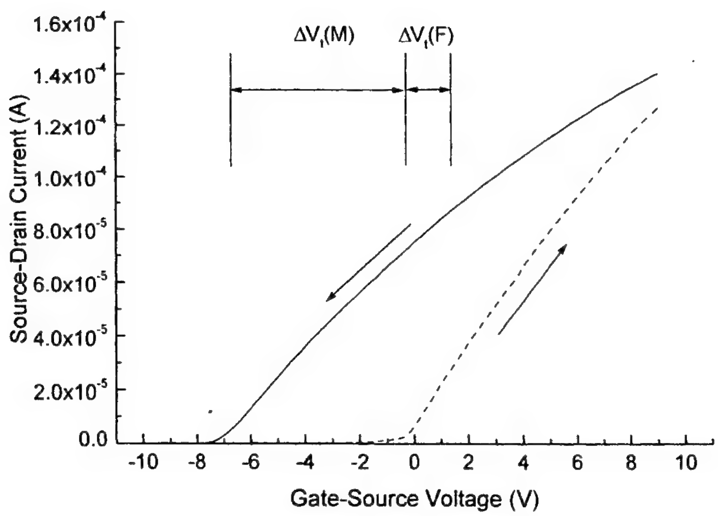


Figure 3. Protonated MOSFET data for a 40 nm gate oxide gate length 50 μm, gate width 100 μm. A fixed leakage current of 4 x 10^{-5} A has been subtracted. The source-drain voltage was 0.2 V.

seconds then V_G swept up (up arrow, dashed curve) to + 8 V in ~ 2 seconds. A hysteresis ~ - 7 V is observed between the two curves. Note that for this device, when the protons were placed at the substrate/oxide interface, the effective current at $V_G = 0$ V was ~ 80 μA. With the protons placed at the gate electrode, the current at $V_G = 0$ V was ~ 2 μA. As a memory, then, this device gives a potential on/off current ratio of 40. This could be improved by appropriate doping of the substrate so that I_{ds}(off) ~ 0.

Note that in Figure 3, ΔV_t(M) is the threshold shift of the transistor due to the mobile charges. ΔV_t(F) is indicated as a possible threshold shift which may be due to fixed (in this case positive) charges present in the oxide. In order to be sure of the presence of this term it is necessary to evaluate the term B in Equation 3 which contains factors involving the substrate and gate electrode material doping. (see reference 2 Chapters 7 and 8 for a detailed discussion of this term). For our devices this value is typically ~ + 1 V so that the positive fixed oxide charge shift is ~ - 1 V.

Radiation Effects

The primary goal of this part of the contract was to examine the radiation hardness of the protonated MOSFET devices. There are two effects to be considered:

a) radiation hardness of the substrate/gate oxide interface

b) radiation hardness of the protons themselves (for example, loss of protons, and hence data, by elimination of protons in the radiation cascade).

We will not address the former question since we have published already data in the literature[6] which demonstrates that the devices are relatively radiation <u>insensitive</u> in terms of the substrate/oxide interface – this insensitivity is exlained by the absence of H based passivation of

the interface in the protonated devices. (Note that in the conventional model, radiation sensitivity of the interface is attributed to depassivation of the interface by release of bonded hydrogen following the radiation process.)

Influence of radiation on the protons

In order to study this phenomenon, protonated MOSFETs were mounted in the ARACOR X-ray source. Prior to irradiation, we measured the hysteresis due to mobile species and the threshold voltage which included positive fixed oxide charge (see above). For the devices studied, the fixed oxide charge threshold voltage shift ($\Delta V_t(F)$ – see Figure 3) was ~ - 1 V giving a threshold voltage when the protons were at the gate electrode/oxide interface ~ 0 V. The mobile proton threshold voltage shift ($\Delta V_t(M)$- see Figure 3) was –1.2 V for one device and – 2.3 V for the other. The difference in magnitude was due simply to the number density of protons in the gate oxide of each device. The devices were then subjected to a 1 MV cm^{-1} polarizing bias for 60 seconds designed to place the mobile protons at the substrate/oxide interface. With the gate electrode floating, the device was then irradiated. Following irradiation to the chosen dose two measurement schedules were carried out:

a) the I_{ds} versus V_G curve was measured rapidly by sweeping from positive to negative voltage in ~ 2 sec. without any prior bias applied.

b) the I_{ds} versus V_G hysteresis was measured after applying first a positive bias for 60 sec. then sweeping from positive to negative voltages. Subsequently, the gate was negatively biased and, after 60 sec., the I_{ds} versus V_G curve measured by sweeping from negative to positive voltage.

The purpose of the first measurement (a) and its comparison with the first curve of (b) was to obtain an I_{ds} curve which would indicate whether or not the protons had **moved** during the process of irradiation. The purpose of the measurement cycle in (b) was to ascertain, from the magnitude of the mobile species hysteresis, if any of the protons had been **eliminated** during the irradiation (for example, by trapping of electrons generated in the radiation cascade). Finally, from the measurement of the negative to positive voltage sweep in (b) it was possible to ascertain

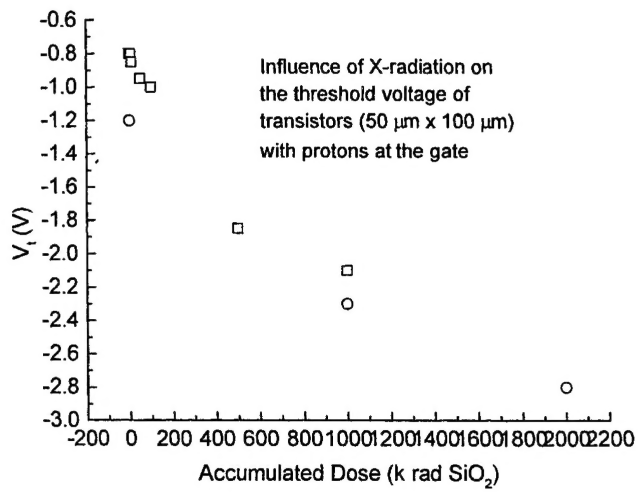


Figure 4. Radiation induced threshold voltage shift in protonated MOSFETs (40 nm gate oxide, 50 μm x 100 μm) due to positive fixed oxide charge generation.

the threshold voltage shift in the "absence" of protons (when they were placed at the oxide/gate electrode interface) and so estimate the effect of irradiation on the oxide itself. For the devices studied here we were unable to measure any reduction in the magnitude of the mobile protons induced hysteresis ($\Delta V_t(M)$) for doses up to 2 Mrad (SiO_2) (i.e. no loss of protons due to capture of electrons in the radiation cascade). We were also able to confirm that up to this dose, there

was no measurable data loss (i.e. drift of protons away from the interface where they were placed initially but without annihilation due to electron capture). The generation of fixed oxide charge in the oxide was detected, however, and the dose dependence is shown in Figure 4. We have previously measured fixed oxide charge generation in the types of oxides we have used in these experiments (i.e. without protons) and the earlier and present data are consistent with straightforward radiation induced degradation in "unhardened" gate oxides..

Conclusions and Suggestions

We have clearly demonstrated that protonated gate memory transistors can be manufactured using standard Si based technology. The effect is present in much thinner oxides than those studied previously[1]and the magnitude of the hysteresis in the I_{ds}/V_G curve is adequate for practical applications. The radiation experiments carried out in the context of this contract clearly demonstrate that the protons themselves are very radiation hard. There is no significant loss of protons up to 2 Mrad of radiation and there is no "data loss" either as defined by the number of protons remaining at an interface as a function of dose. Not to be neglected about these devices are the following points however:

a) the devices are not truly non-volatile since it has been demonstrated[5] that retention of data is not "infinite" (i.e. not on a scale of years).

b) switching time is likely to be a problem for two reasons – 1) scaling to very thin oxides (~ 5 nm) indicates that the fastest time will be ~ tens of microseconds for reasonable electric fields 2) there is a problem in defining what one might call the switching time given the diffusive nature of the motion of the protons in the oxide which means that

there is no clear, simply defined "on/off" state change. Detailed discussion of the nature of switching is found in reference 5.

c) One cannot neglect the fact that although the protons are apparently radiation insensitive, the gate oxide itself is not, and therefore radiation-induced shift of the I_{ds}/V_G curve itself due to charge trapping in the oxide will occur (as shown in Figure 4). The importance of the displacement may be possibly minimized by engineering or by appropriate choice of substrate doping etc. One "simply" needs to ensure that in the off state there is no I_{ds} whereas in the on state, I_{ds} is finite.

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